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Speckle Noise Attenuation in Coronagraphy and High-Contrast Imaging

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The Spirit of Lyot Conference
Berkeley, CA, United States
June 4, 2007 through June 8, 2007

Disclaimer

Speckle Noise Attenuation in Coronagraphy and High-Contrast Imaging

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-Detecting Exoplanets

-Speckle noise attenuation techniques with specialized observation schemes and post-processing algorithms

-Current On-sky performances

-The future with GPI & SPHERE

-Conclusion

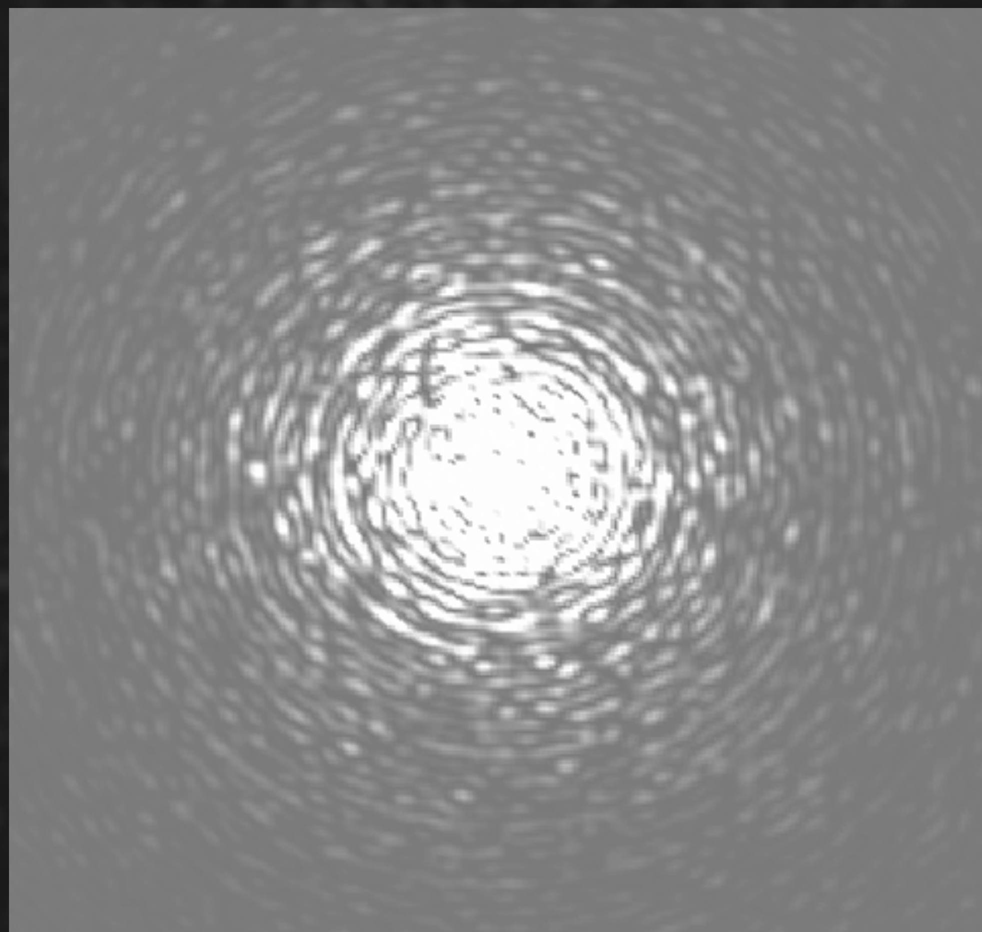
UC Berkeley
June, 2007
Lyot Conference

Work was performed under the auspices of US DOE, NNSA, by the Univ. California, LLNL, under contracts No. W-7405-Eng-48.

Detecting Exoplanets

Planets are hidden under a sea of look-alike speckles

Planet?

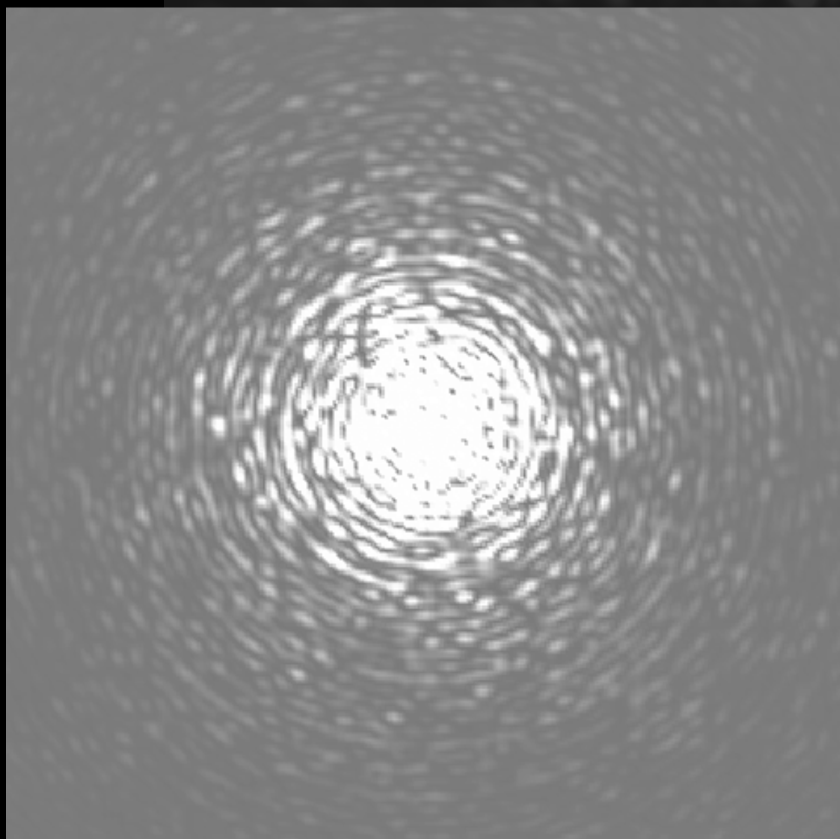


<u>But planets are not speckles!</u>: not coherent (Baudoz talk), different spectrum (SSDI), not fix with stellar PSF (ADI) & different polarization.

Simultaneous Spectral Differential Imaging

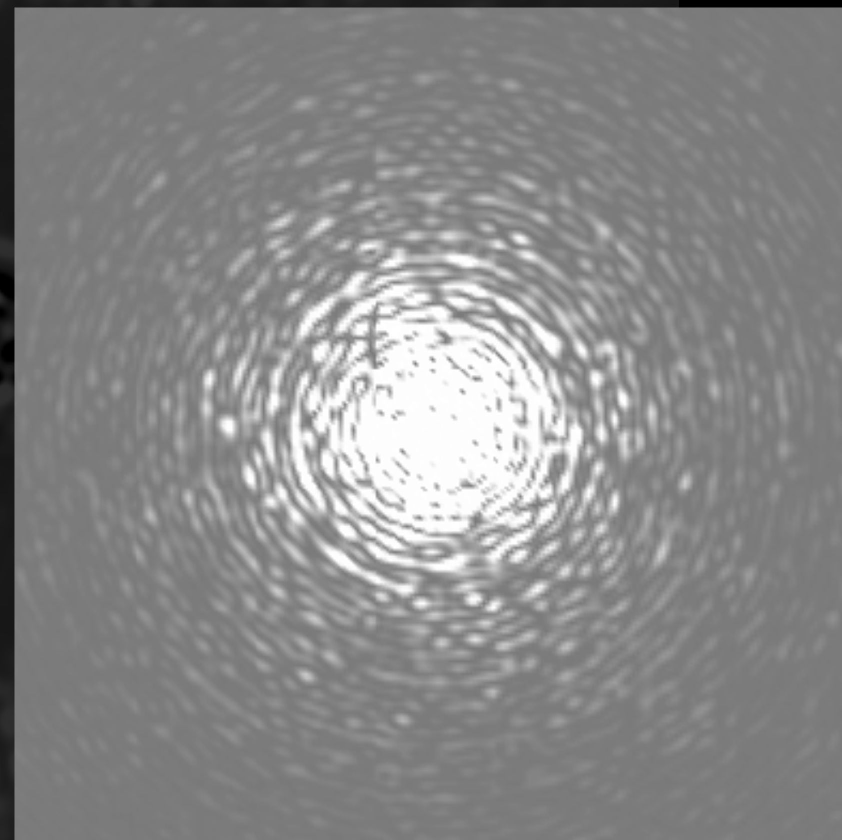
(assuming Fraunhofer diffraction)

Raw spectral data cube



Speckle location is chromatic

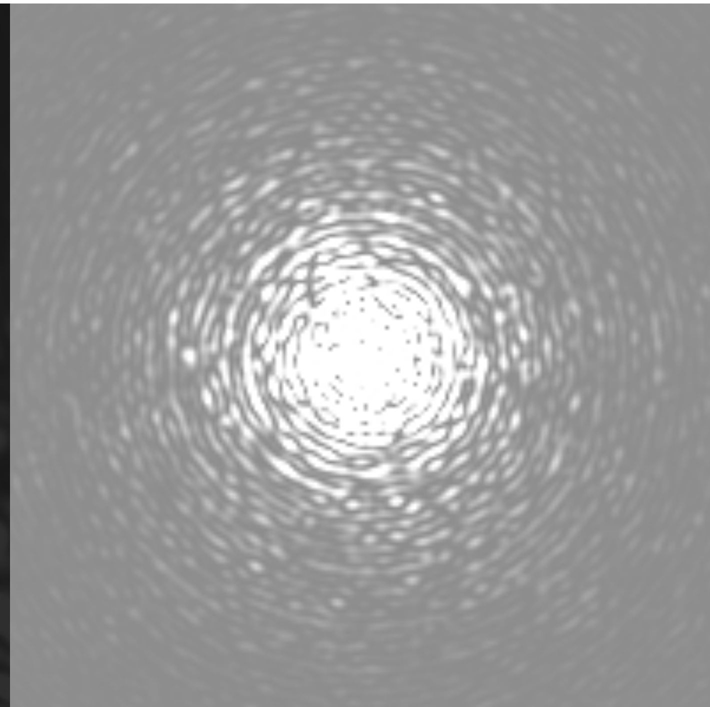
Spatially scaled spectral data cube

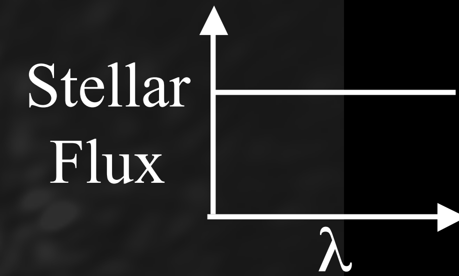


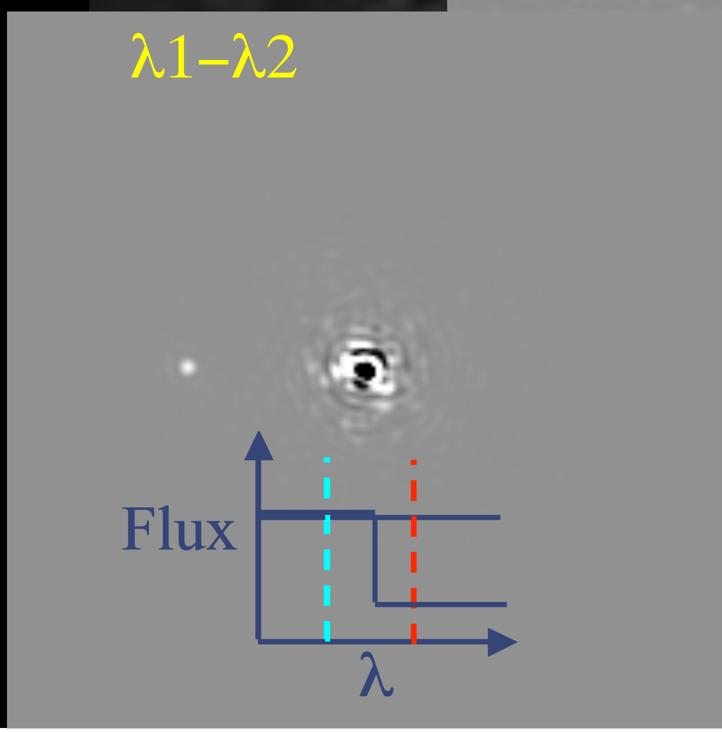
Planet location is chromatic

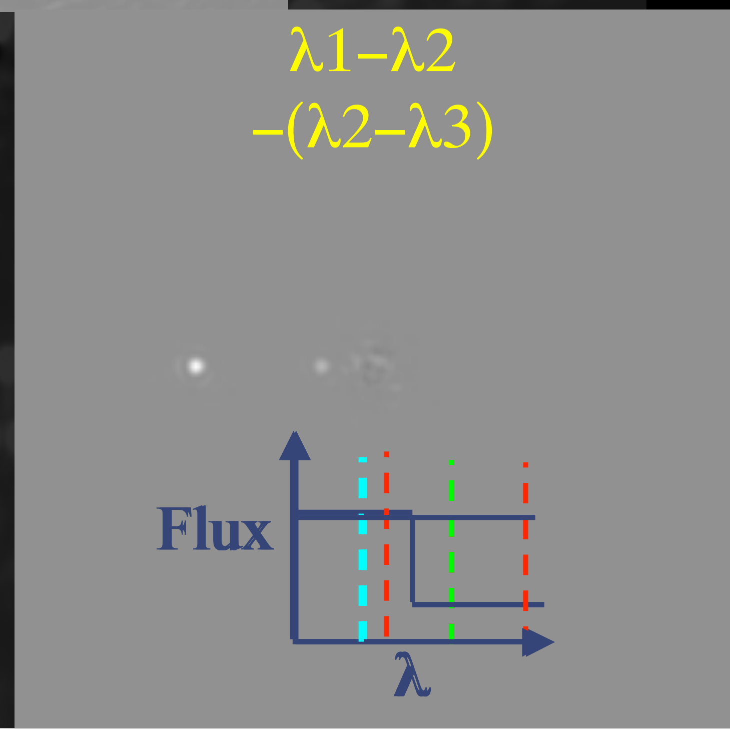
Racine et al. 1999, Marois et al. 2000, Marois 2004, Marois et al. 2005

Combining images
=
speckle attenuation









SSDI speckle noise attenuation predictions

Following: (Bloemhof et al. 2001, Sivaramakrishnan et al. 2001, Perrin et al. 2002, Bloemhof 2003)

PSF $I = |\ TF\ (A\ e^{i\phi})|^2$ A = amplitude
ϕ = phase

Taylor expansion + ….

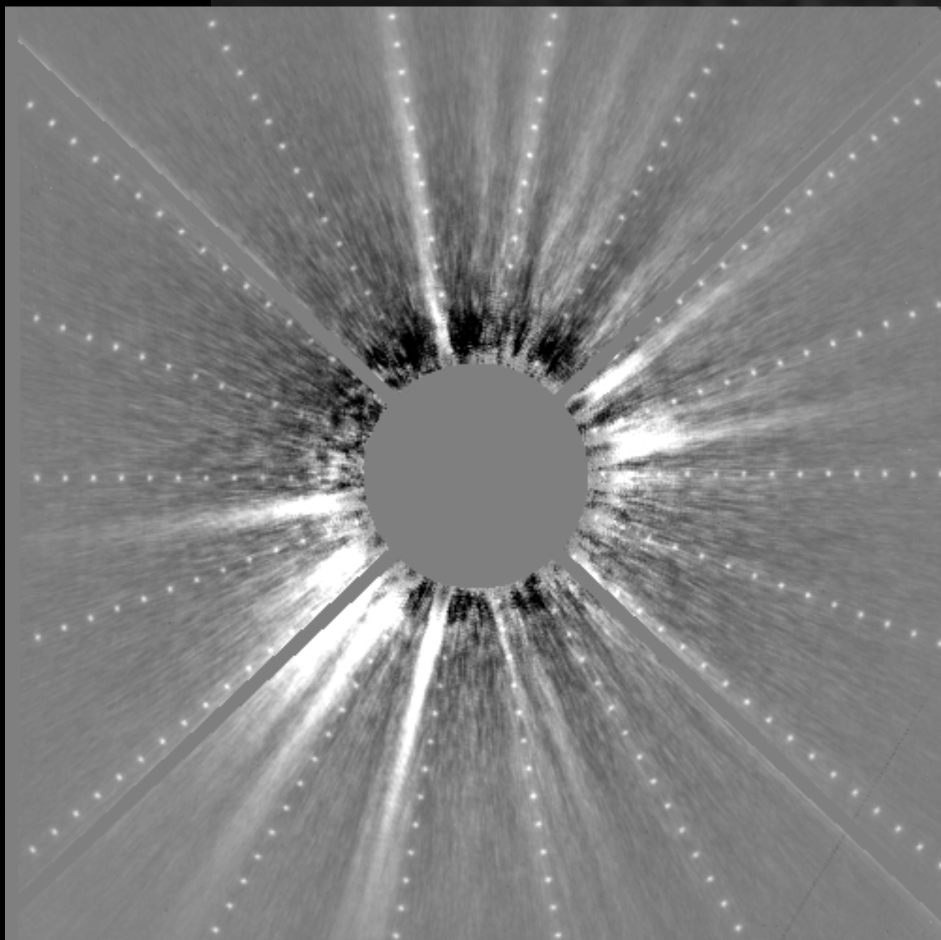
Simple difference attenuation $[\Delta N/N]_{SD} = \Delta\lambda_{2,1}/\lambda_2$ 30x

Double difference attenuation $[\Delta N/N]_{DD} = \Delta\lambda_{3,2}/\lambda_3\ [\Delta N/N]_{SD}$ 1100x

\+ more wavelengths… >> 1100x

Flat field problem at some point

Angular Differential Imaging



In theory "perfect", but in practice limited by quasi-static speckle time evolution (seeing, thermal & flexure).

Combining images acquired at the same wavelength but with different field angles to subtract quasi-static speckles.

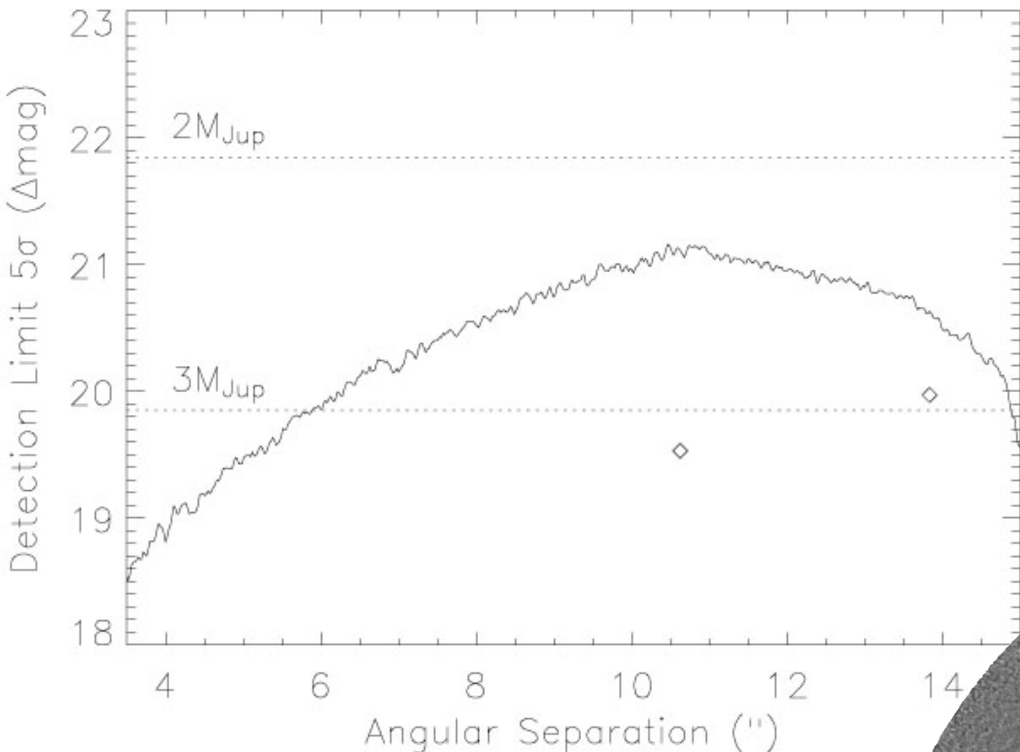
HST: Roll subtraction (0th order ADI).

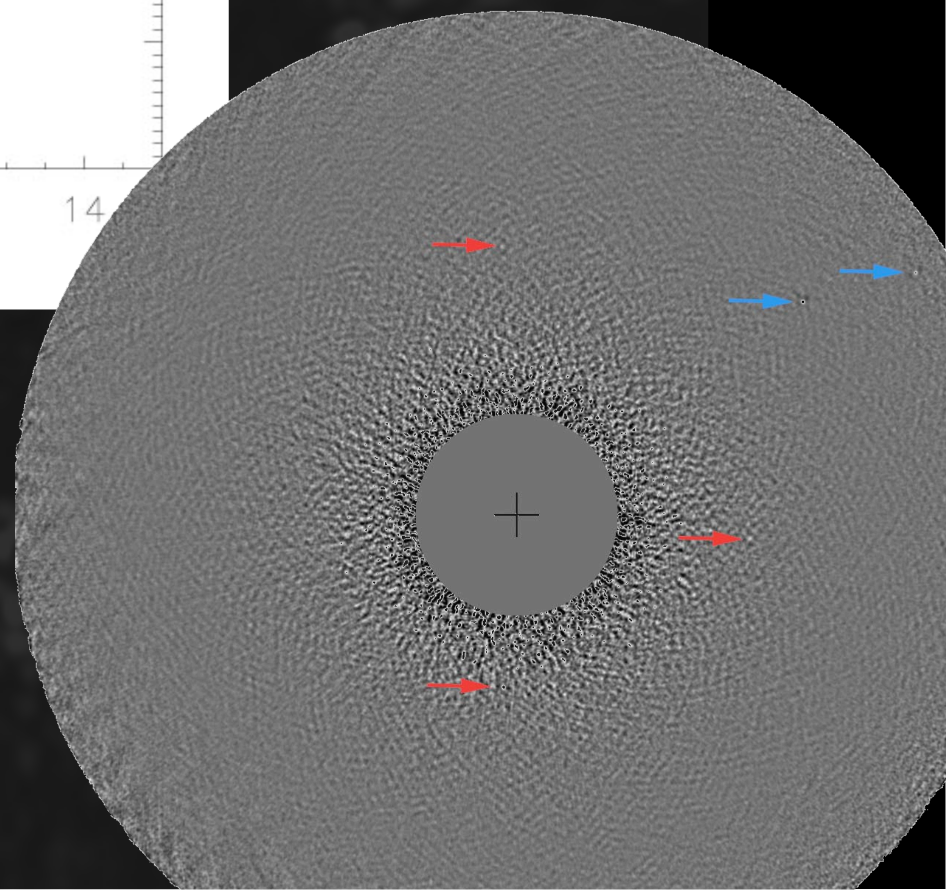
Gemini: Full ADI (many angles, Cass focus).

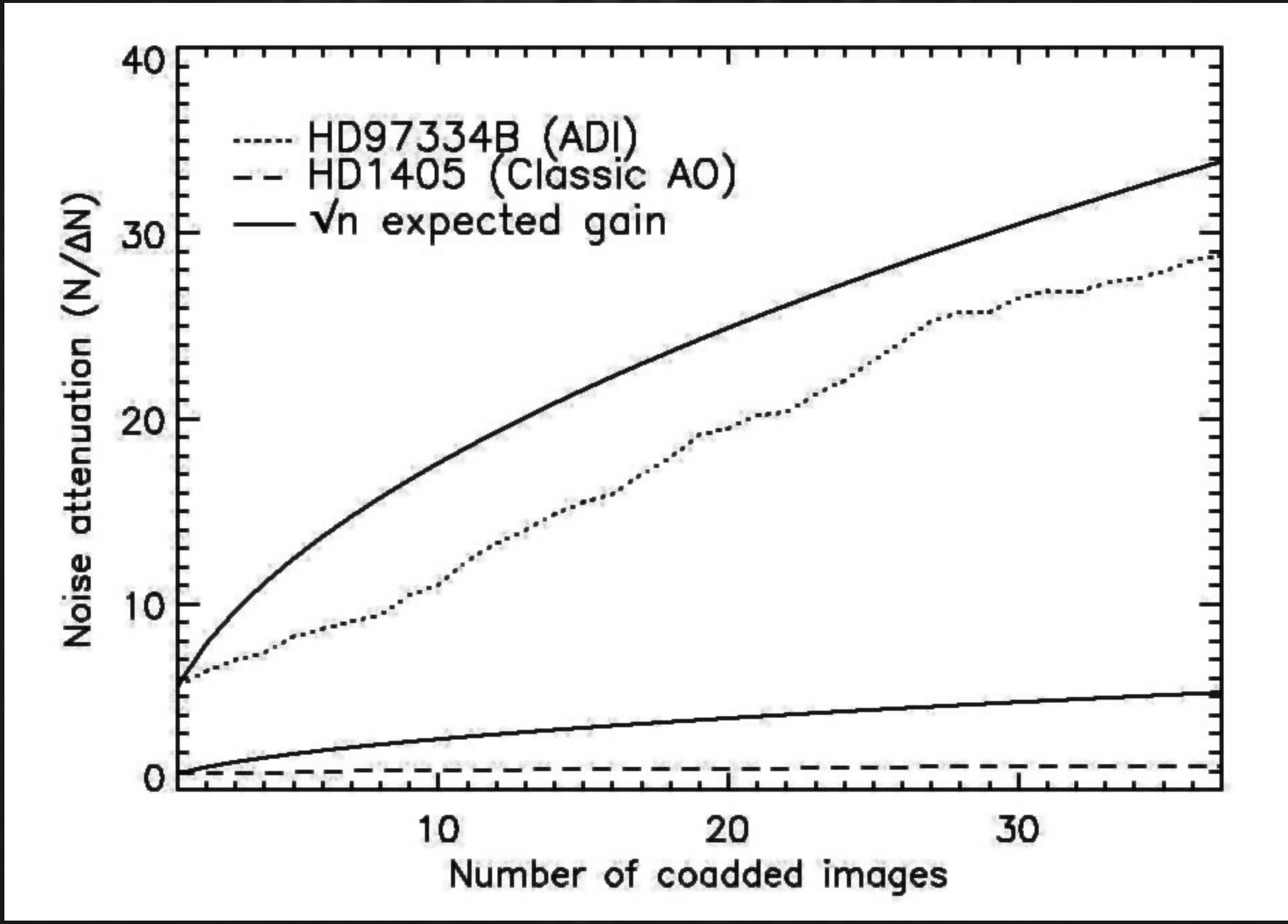
Lyot: Multi-rotation-plane ADI (Nasmyth focus).

SDI: partial ADI (Nasmyth focus), single roll subtraction (force instrument rotation leaves some interference quasi-static speckle terms), but time res quasi-static speckle smoothing due to Nasmyth focus location.

Marois 2004, Liu 2004, Marois et al. 2006, Lafreniere et al. 2007


2MJup
3MJup
Detection Limit 5σ (Δmag)
Angular Separation (")
23
22
21
20
19
18
4
6
8
10
12
14

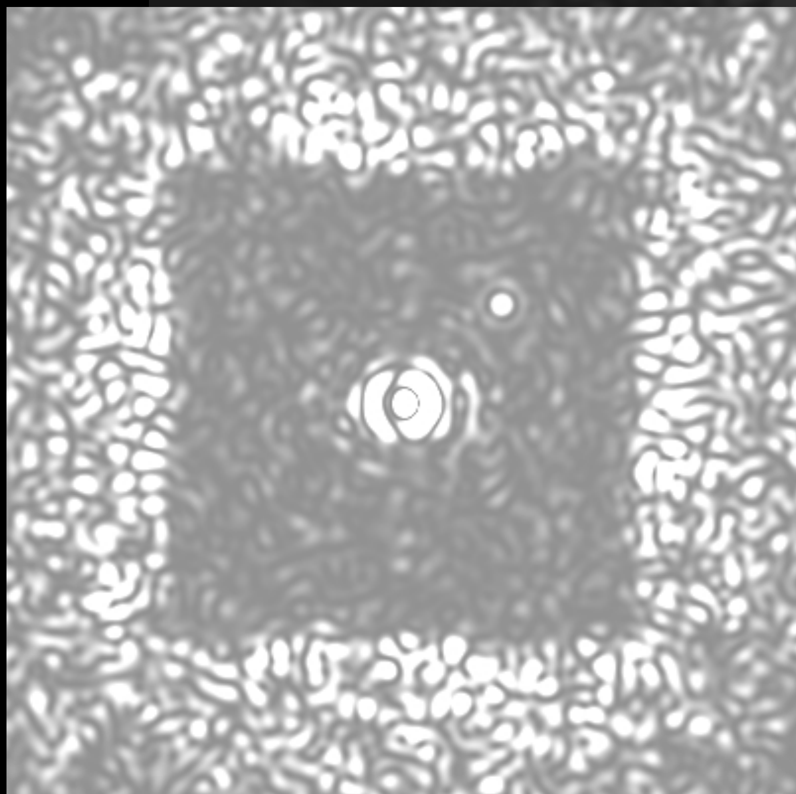




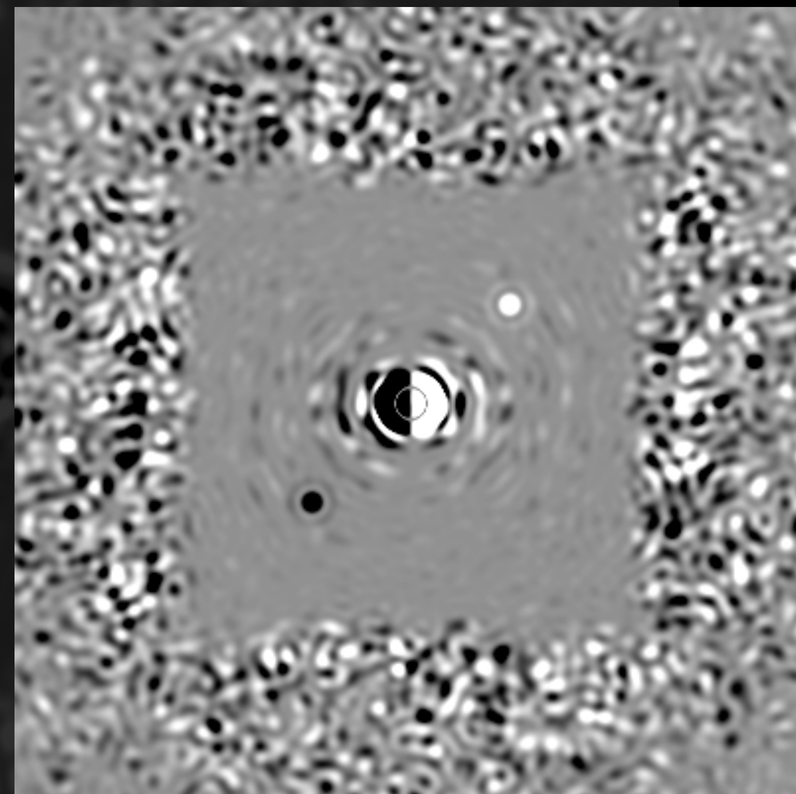
HD97334B (ADI)
HD1405 (Classic AO)
√n expected gain
Noise attenuation (N/ΔN)
Number of coadded images
0
10
20
30
40

Speckle Symmetry

At high Strehl ratios & with coronagraphy, expected speckle symmetry



Coronagraphic image



Coronagraphic image – 180 rot

With 5 mas tilt

Perrin et al. 2003, Marois 2004

On-Sky/Laboratory Result

SSDI: TRIDENT, AIC, SDI, NICI, HiCIAO

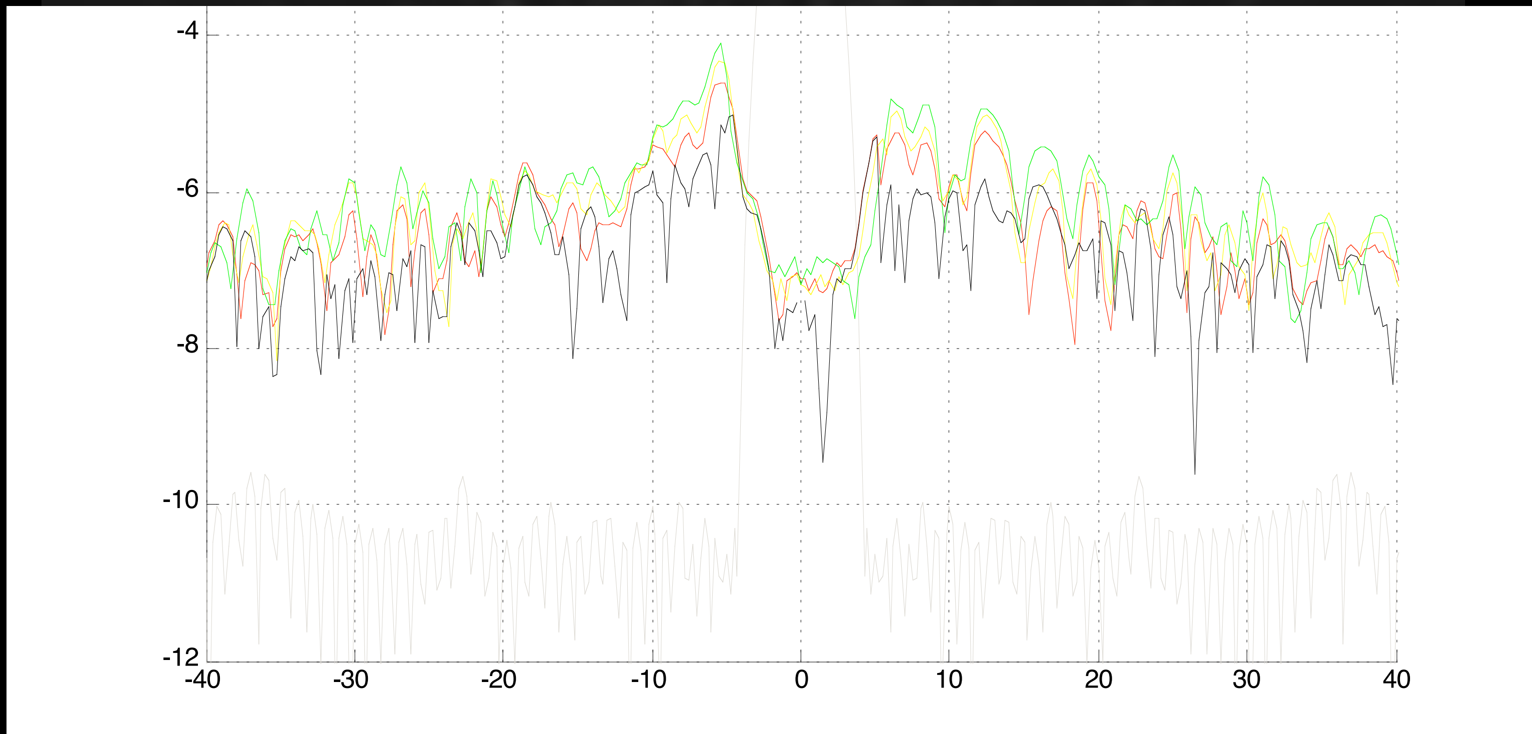
ADI: HST, NIRI, NIRC2, Lyot, Clio, SDI, NICI

Speckle symmetry: ???

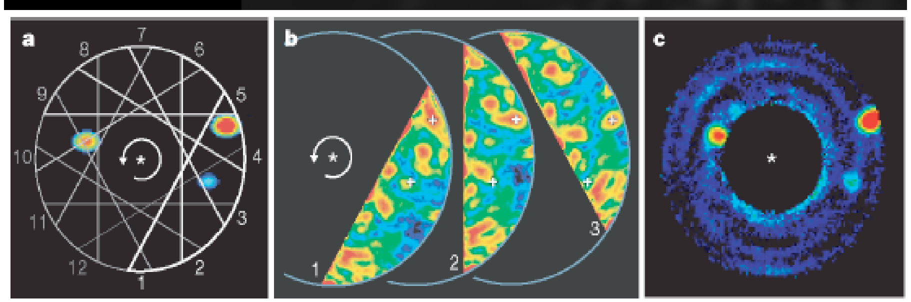
Laboratory

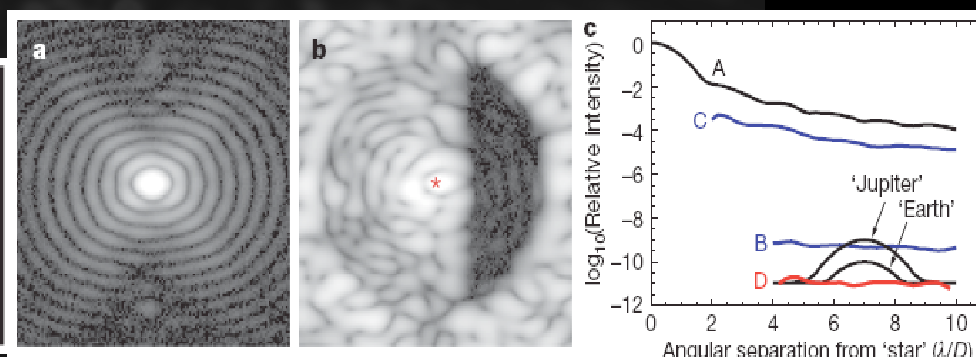
SSDI: TRIDENT/Diffuser/MLA@Univ. of Montreal, TPF @ Princeton & JPL
ADI: TPF @ JPL (Trauger & Traub Nature paper, 48 rot angles)

SSDI: Princeton & JPL TPF (see Ruslan talk)



ADI: JPL TPF (see Trauger & Traub talks)





SSDI@CFHT & VLT

Limitations:
-Non-common path optics in BS & filters.

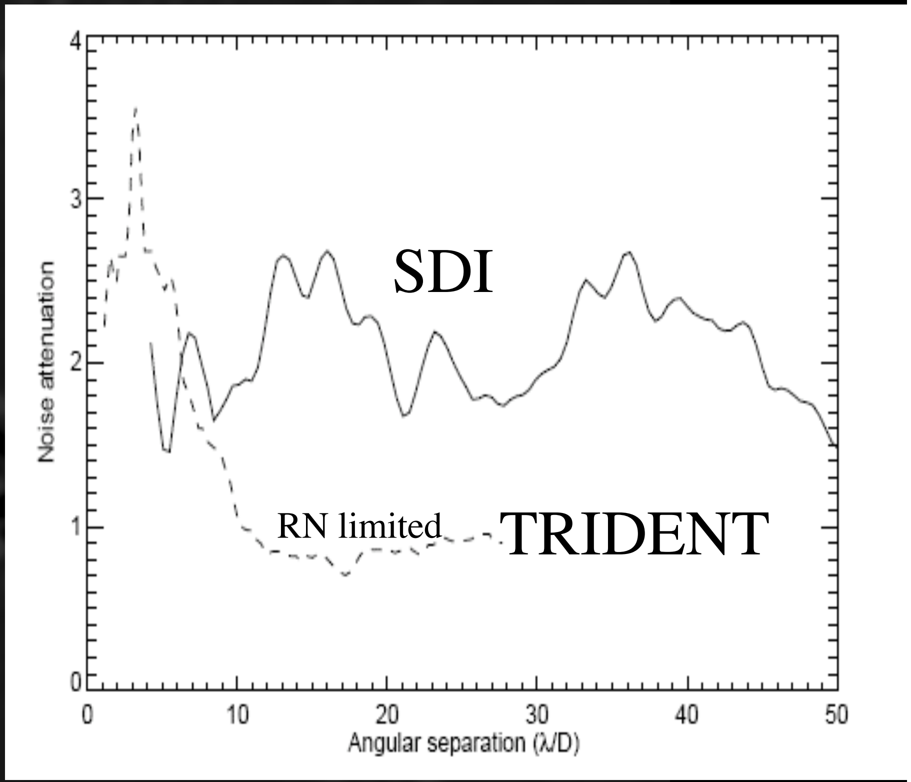
Soln.: MCDA/diffuser.

(Marois et al. 2004, Lafreniere et al. 2007)

-Fresnel phase-induced amplitude aberrations from out-of-pupil-plane optics.

(Marois et al. 2006, Shaklan et al. 2006)

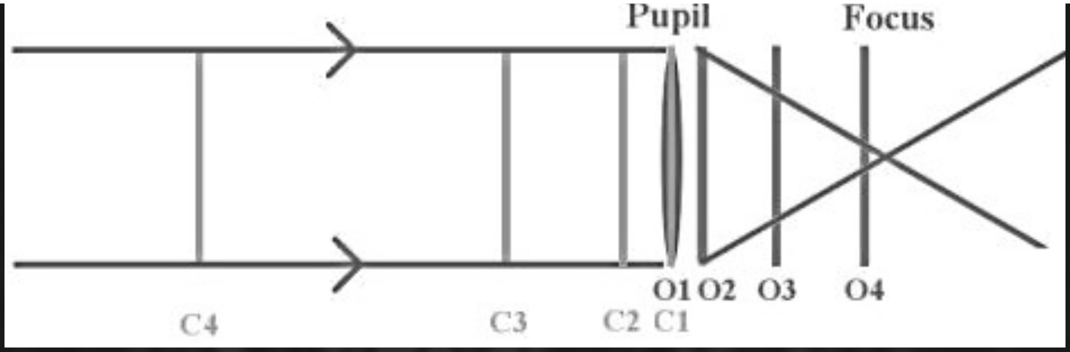
Soln.: Good o-o-p-p optics.



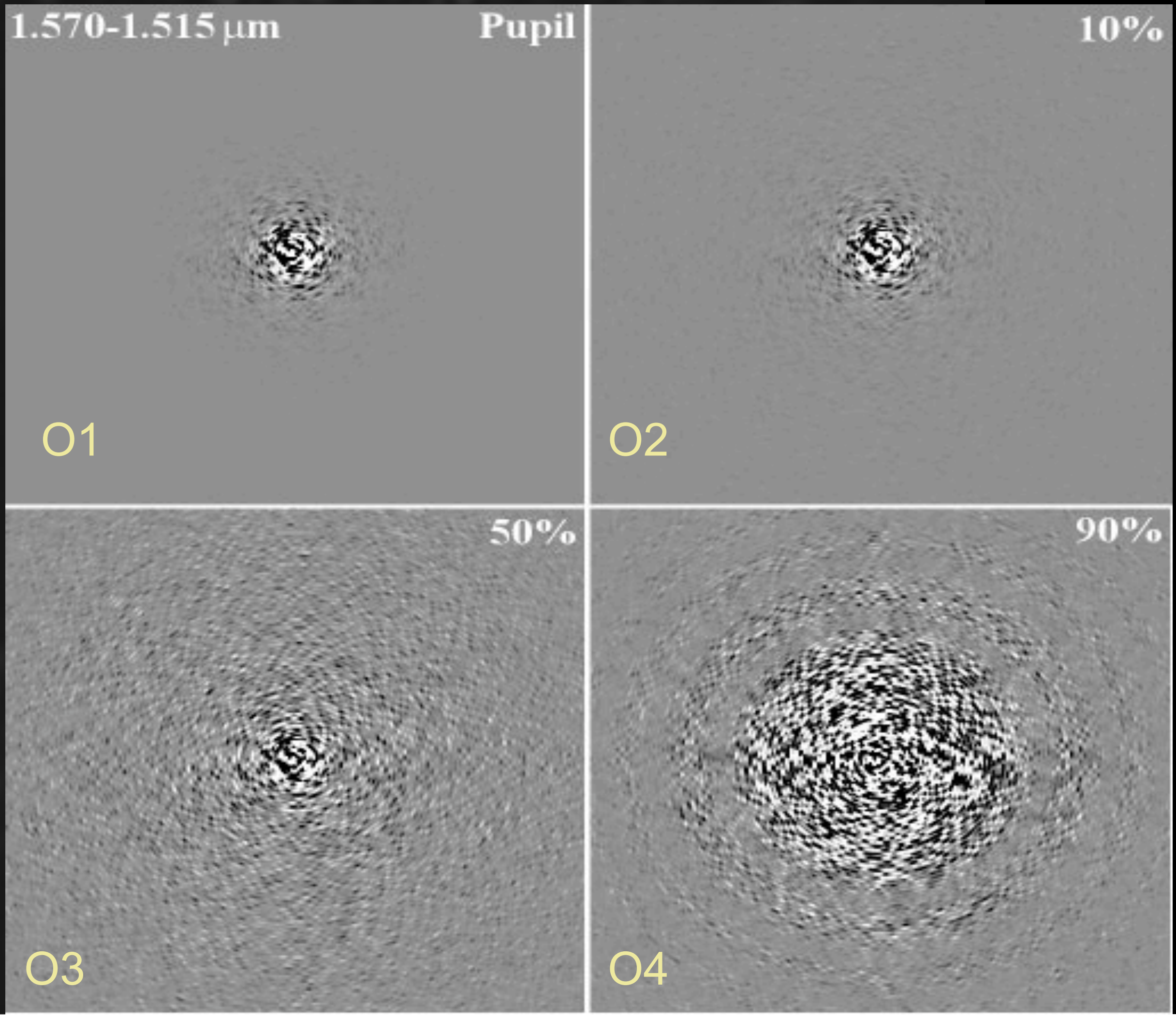
From Lafreniere et al. 2007

Simple difference only

SSDI is good for near pupil-plane conjugated aberrations (tel. pupil, DM & atm)

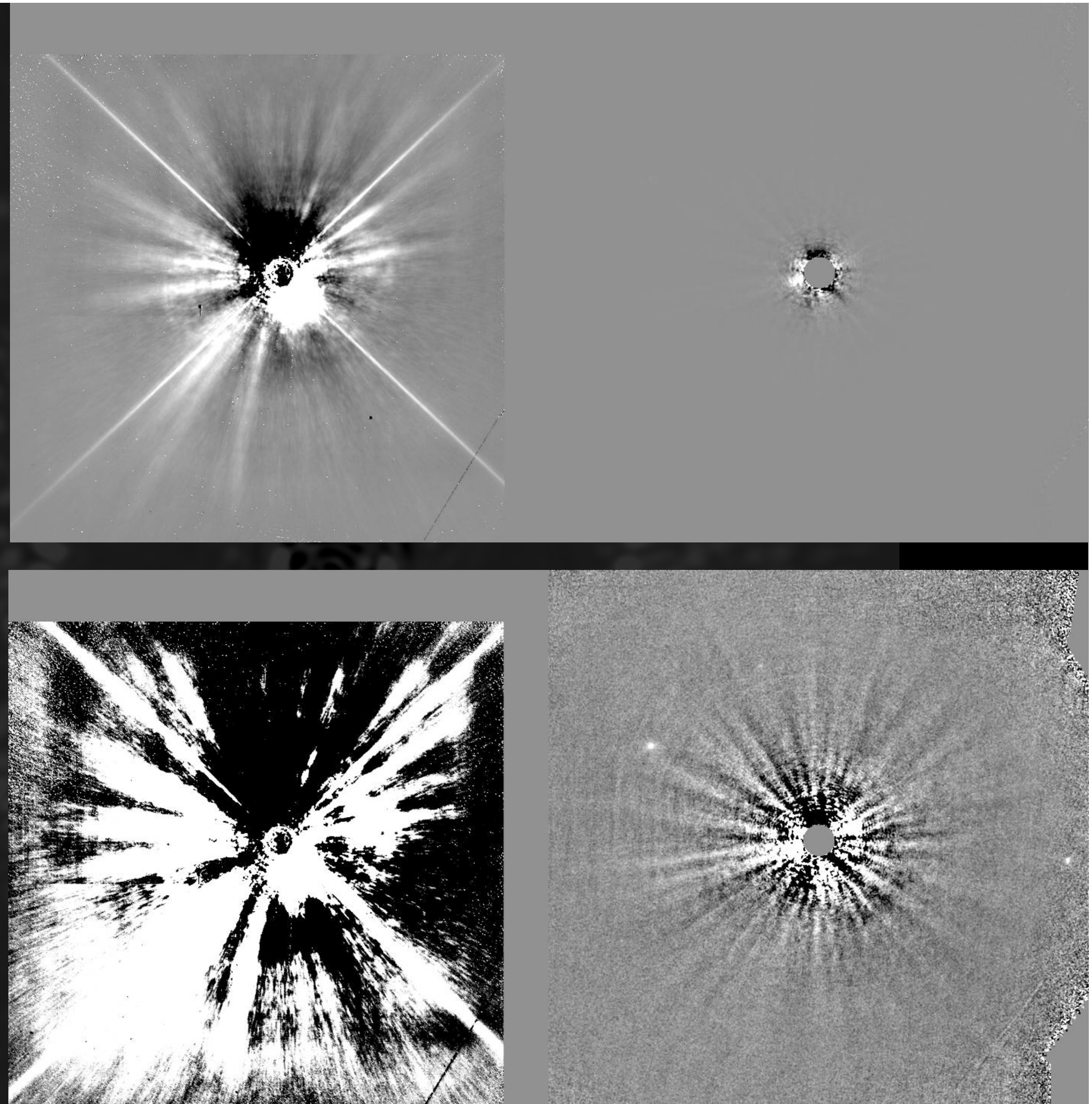


Simple difference



Phase to amplitude aberration mixing can significantly reduce SSDI speckle noise suppression performances if the aberration plane is close to focal plane.

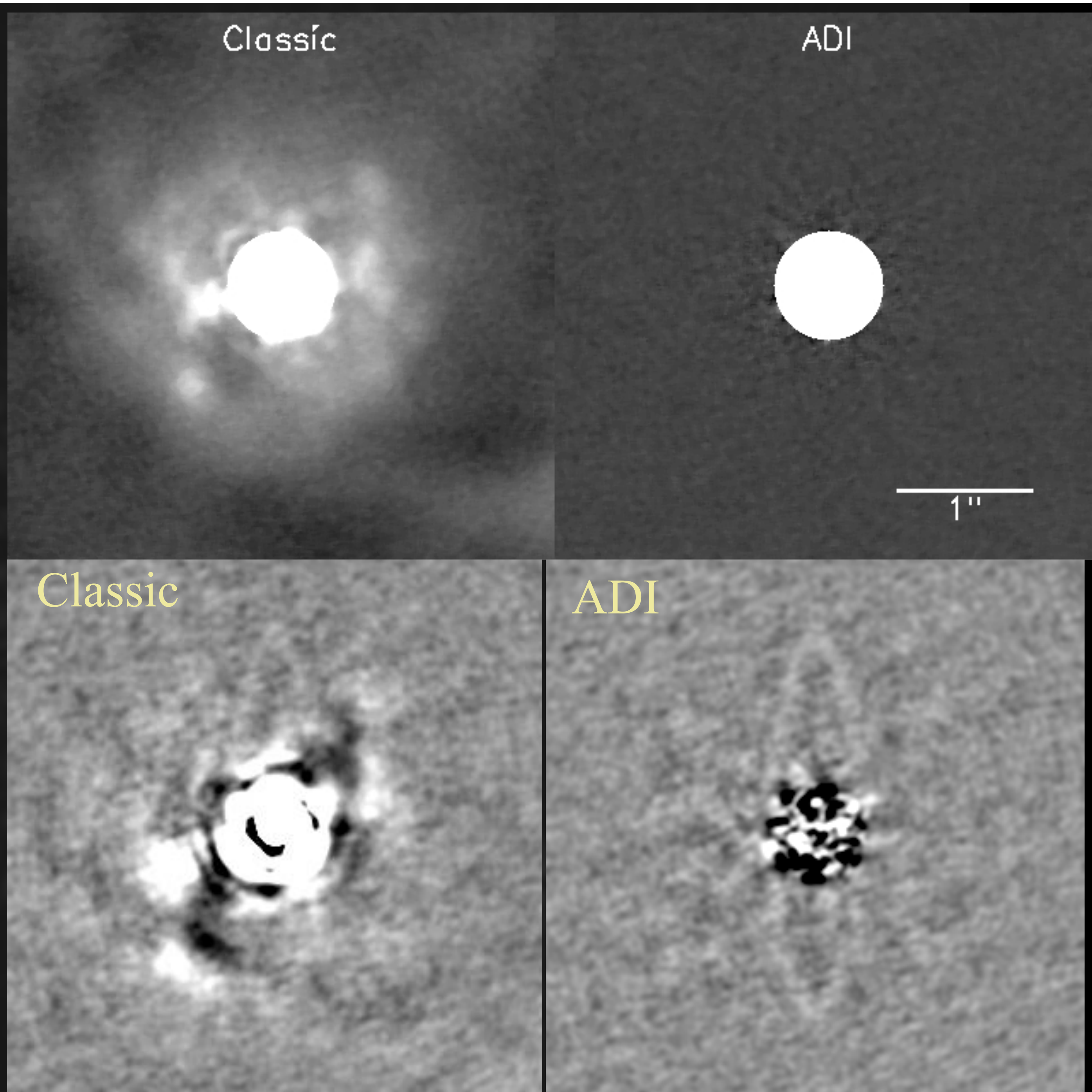
ADI@Gemini



See Lafreniere talk for GDPS survey summary

ADI@Keck
At L’

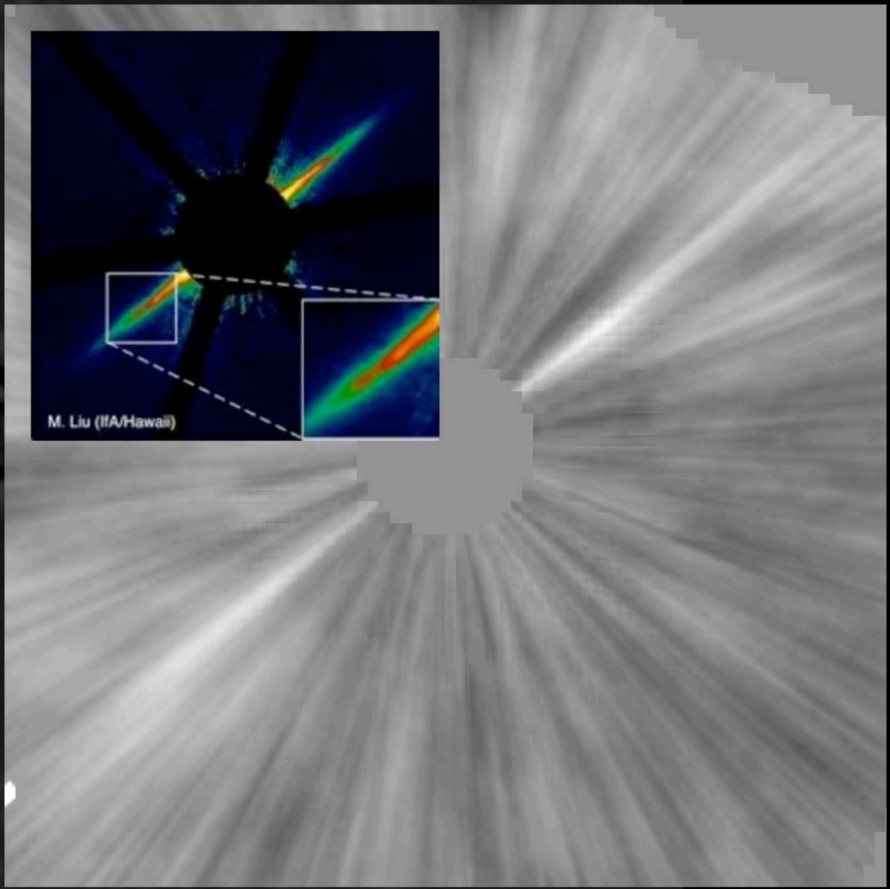
HR4796



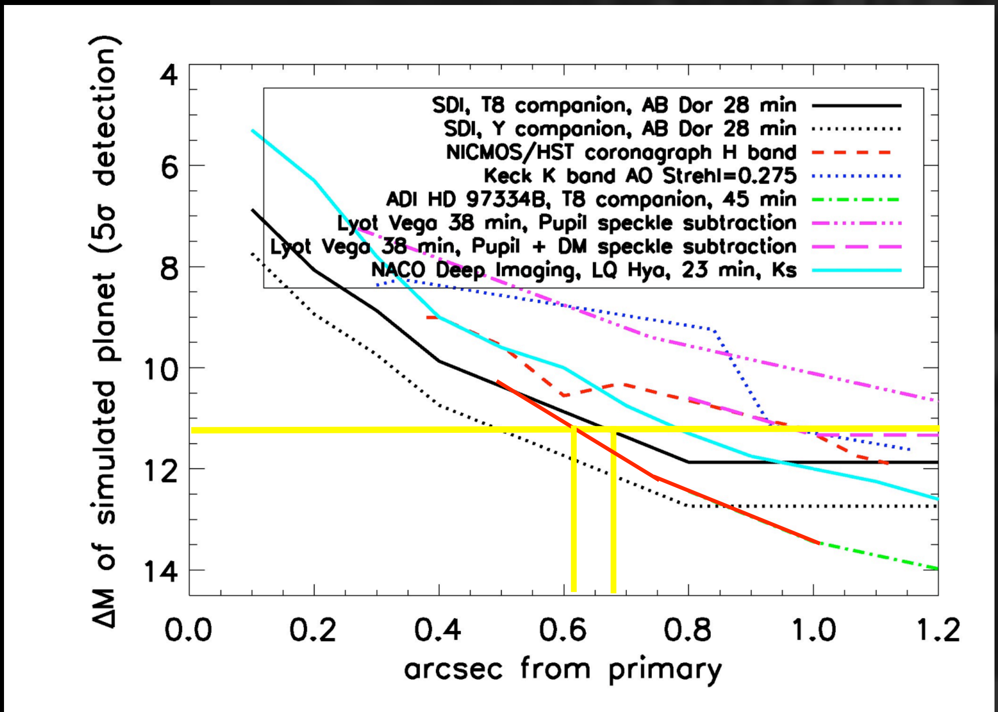
ADI@Keck

Au MIC without ADI (L')

Au MIC with ADI (L')



On-Sky performances: Ground-based



Adapted from Biller et al. 2007, in press

SDI (narrow band) curve is corrected (~2.2x) for T8 spectrum but not the other curves (some K, H or methane 6.5% filter).

SDI median target is a K star. For a K3 star (M_H ~ 4.2), and T8 object (~800K), ΔH is ~ 11.3 magnitudes (Baraffe et al. 2003 COND model).

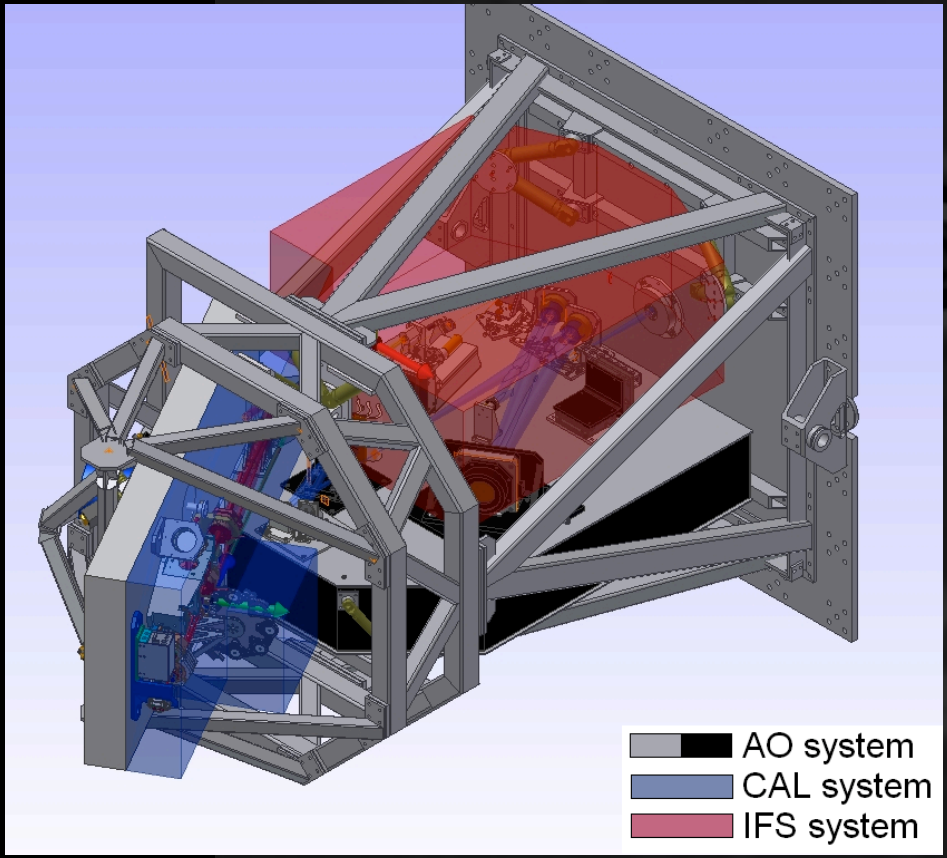
T8 object (800K) around K3 star

T8 corrected (1.8x) ADI curve (from GDPS survey).

The Future with the Gemini Planet Imager (GPI) & SPHERE

Dedicated exoplanet finder instruments for 8-m telescopes

GPI (see Bruce Macintosh talk)



From Darren Erickson, HIA

-Smooth optics (min Fresnel).

-High-order spatially filtered with optimal gain controller fast AO (see Poyneer talk).

-Rémi Soummer APLC Coronagraph (The "Soummer Coronagraph")

-JPL IR CAL interferometer (see Shao talk)

-IFS for acquisition & speckle suppression

Just completed PDR!

GPI polychromatic simulation

Is important because:

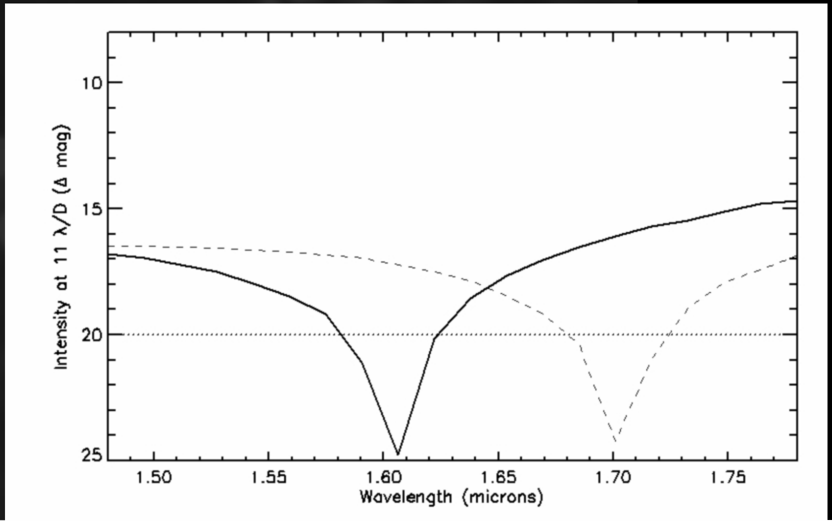
1- DM phase correction not optimal for all science bandpass
2- 1-2h observations are not photon noise limited
3- ADI/SSDI/Symmetry speckle suppression techniques are needed to reach the γ-noise

These speckle attenuation techniques are limited by:

1- Out-of-pupil-plane propagation effects that are producing phase-induced **chromatic** amplitude aberrations.

2- Coronagraph **chromaticity**

Minimizing GPI PSF chromaticity is essential if we want to reach the fundamental γ-noise limit and maximize GPI science deliverables.

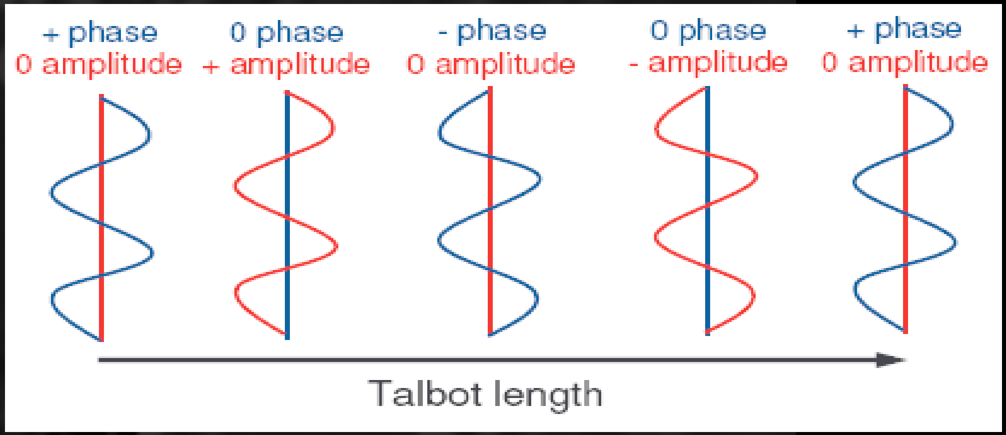


Talbot imaging: phase-induced ampl. errors

-From Fresnel propagation

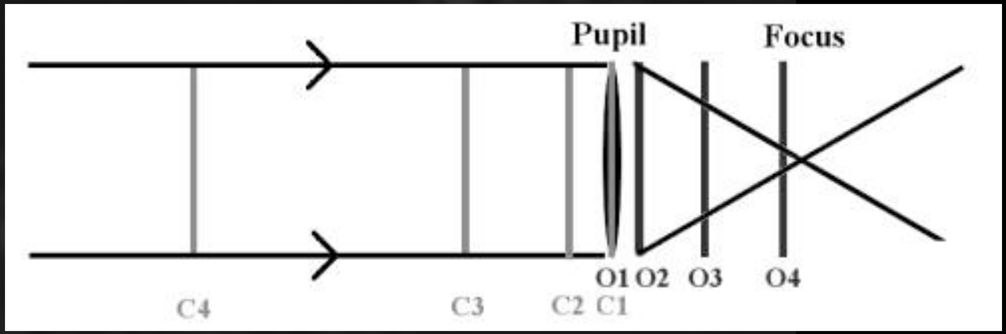
-Valid for:
- -Infinite wavefronts
- -Collimated beam
- -Small aberrations

-Easy to implement



-A pure phase is oscillating between pure phase and a pure ampl. aberration over a length equal to:

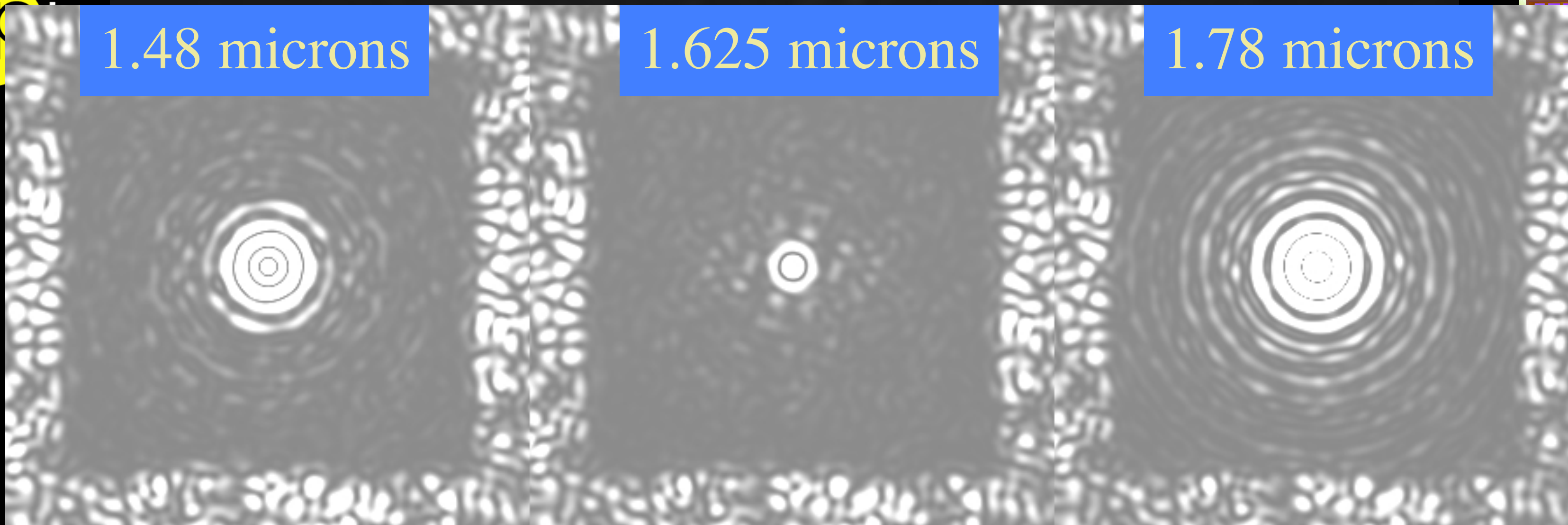
$$\tau_L = 2\Lambda^2/\lambda$$

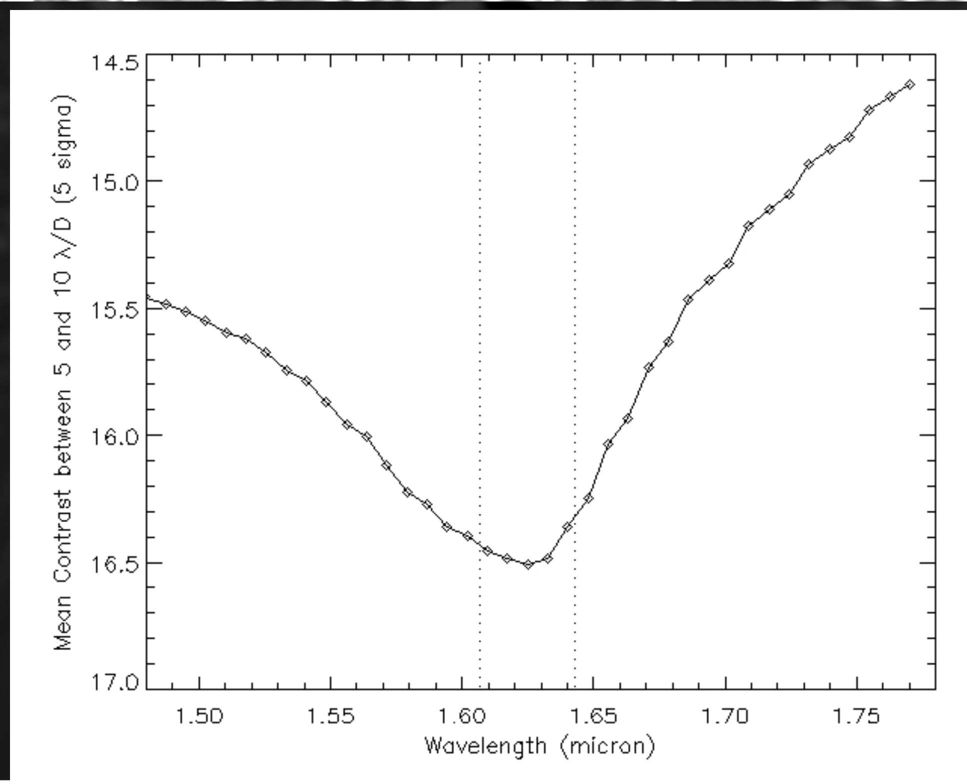


where Λ is the aberration spatial period.

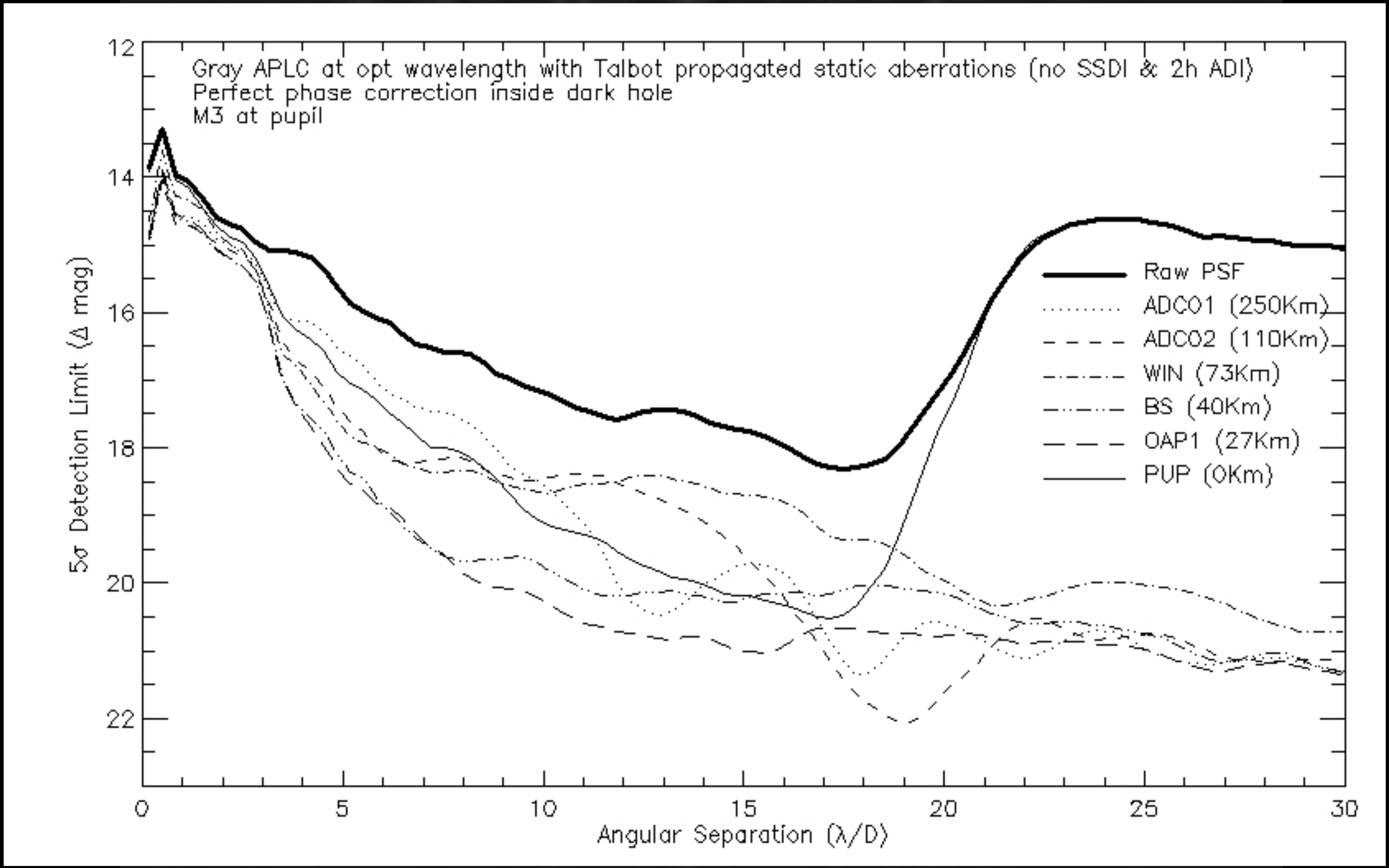
GPI optical surface specification

Surface	Grouped conj. altitude (Km)	True conj. Altitude (Km)	0-4λ/D^{-1} RMS WFE (nm RMS)	4-22λ/D^{-1} RMS WFE (nm)	Ampl. Err WFE %RMS	Total 0-4λ/D WFE (nm RMS)	Total RMS 4-22λ/D WFE (nm RMS)	Total WFE Ampl. error (% RMS)
ADC01*	250	250	7	1.4	0.14	7	1.4	0.14
ADC02*	110	110	7	1.4	0.14	7	1.4	0.14
Window*	73.2	55.7	2.5	0.5	0.1	9.4	1.9	0.22
Ellipse		73.2	5	1	0.1			
OAP3		63.3	5	1	0.1			
OAP4		58.7	5	1	0.1			
Folding flat		67.7	2.5	0.5	0.1			
Beam-Splitter*	40	40	7	1.4	0.14	7	1.4	0.14
OAP1	27	27	5			7	1.4	0.14
OAP2		27.4	5	1	0.1			
M3		17.6	5	14	0.3			
M1	0	0.1	5	50	0.3	8.7	52	0.52
M2		0	5		0.3			
MEMs	0	0	0	0	0	0	0	0


1.48 microns
1.625 microns
1.78 microns


Mean Contrast between 5 and 10 λ/D (5 sigma)
14.5
15.0
15.5
16.0
16.5
17.0
1.50
1.55
1.60
1.65
1.70
1.75
Wavelength (micron)

GPI raw contrast

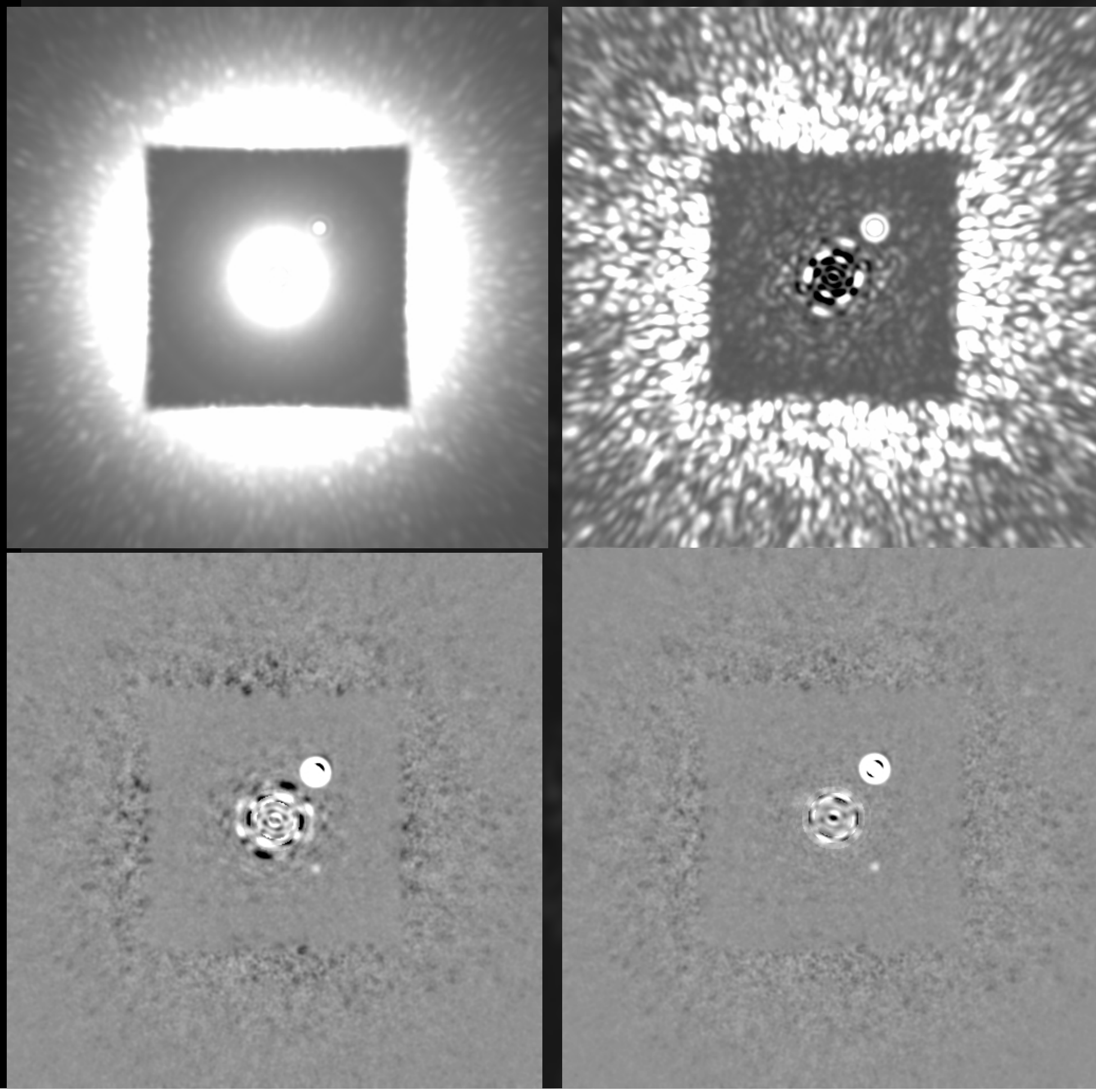


Contribution from each conjugated plane

Long exposures (with atm) and ADI/SSDI

2h raw
H=5
I=6
4%BP

2h speckle noise

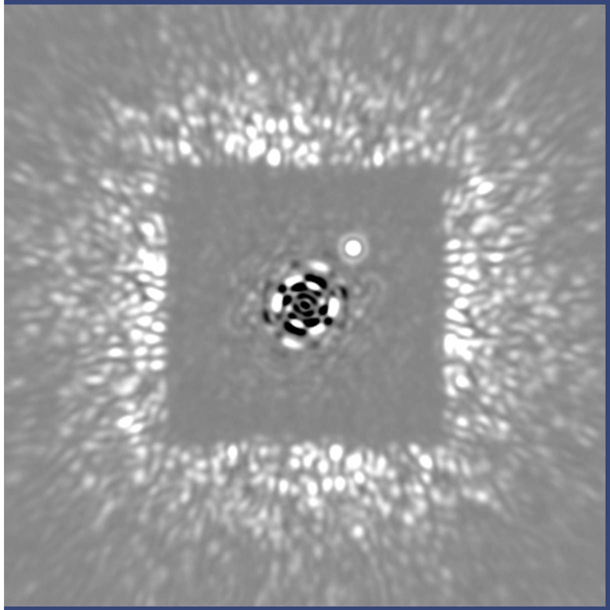


SSDI
SD

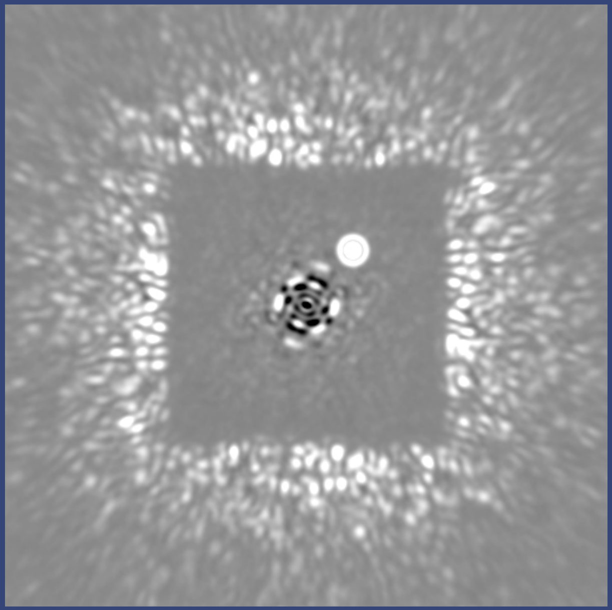
SSDI DD

100 Myr K7V
10 pc
5 & 1 M_{Jup} at 4AU
630K & 310K
ΔH = 12 & 17.4
(T8 spectrum)

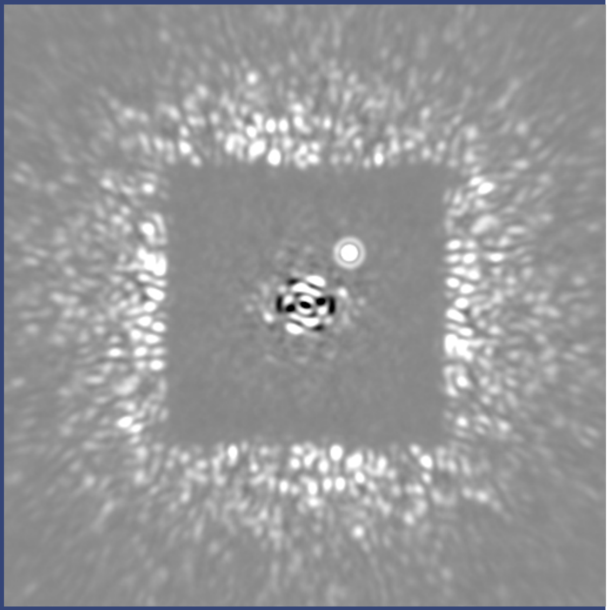
1.515 microns



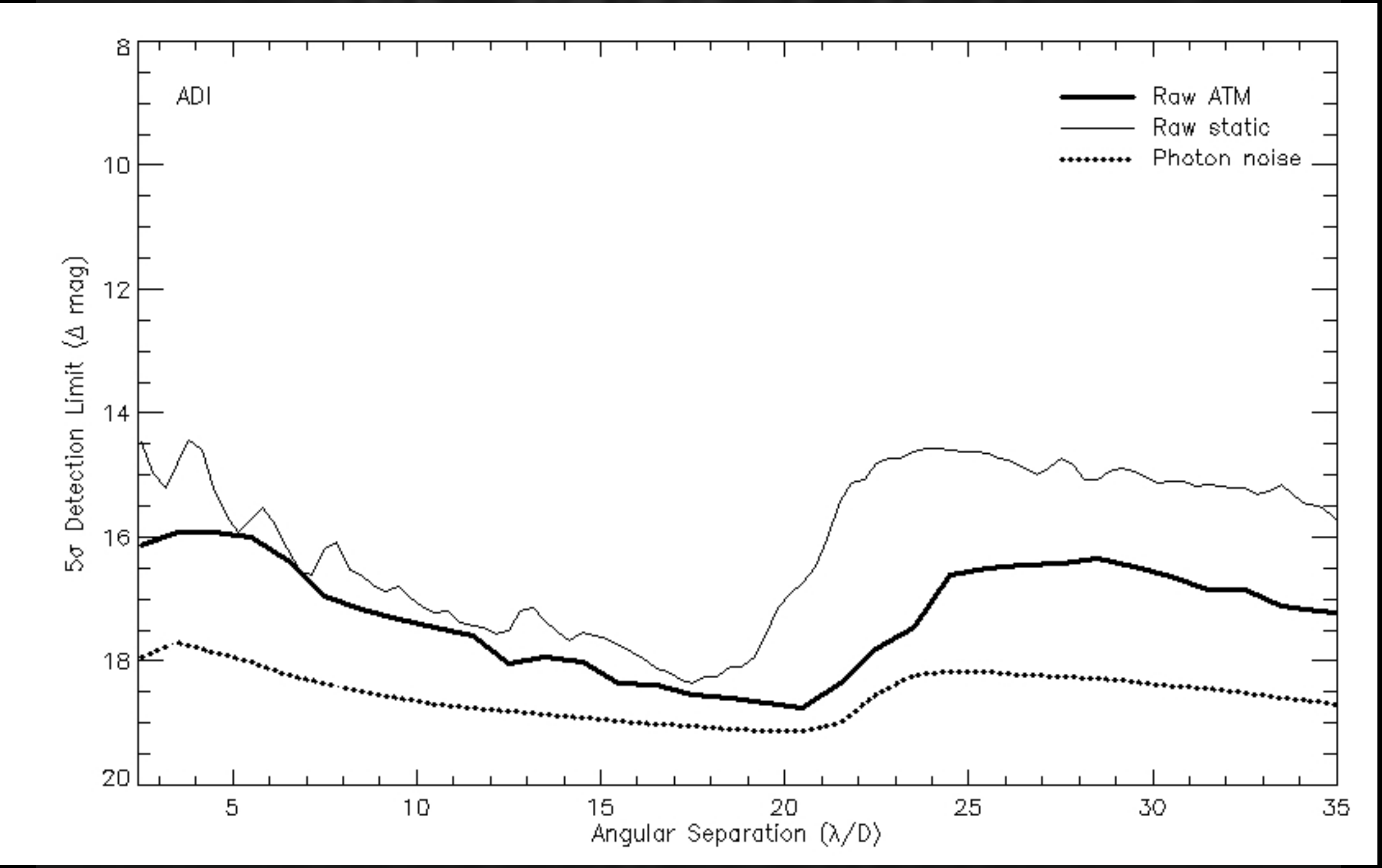
1.57 microns



1.625 microns



Coro opt. wavelength

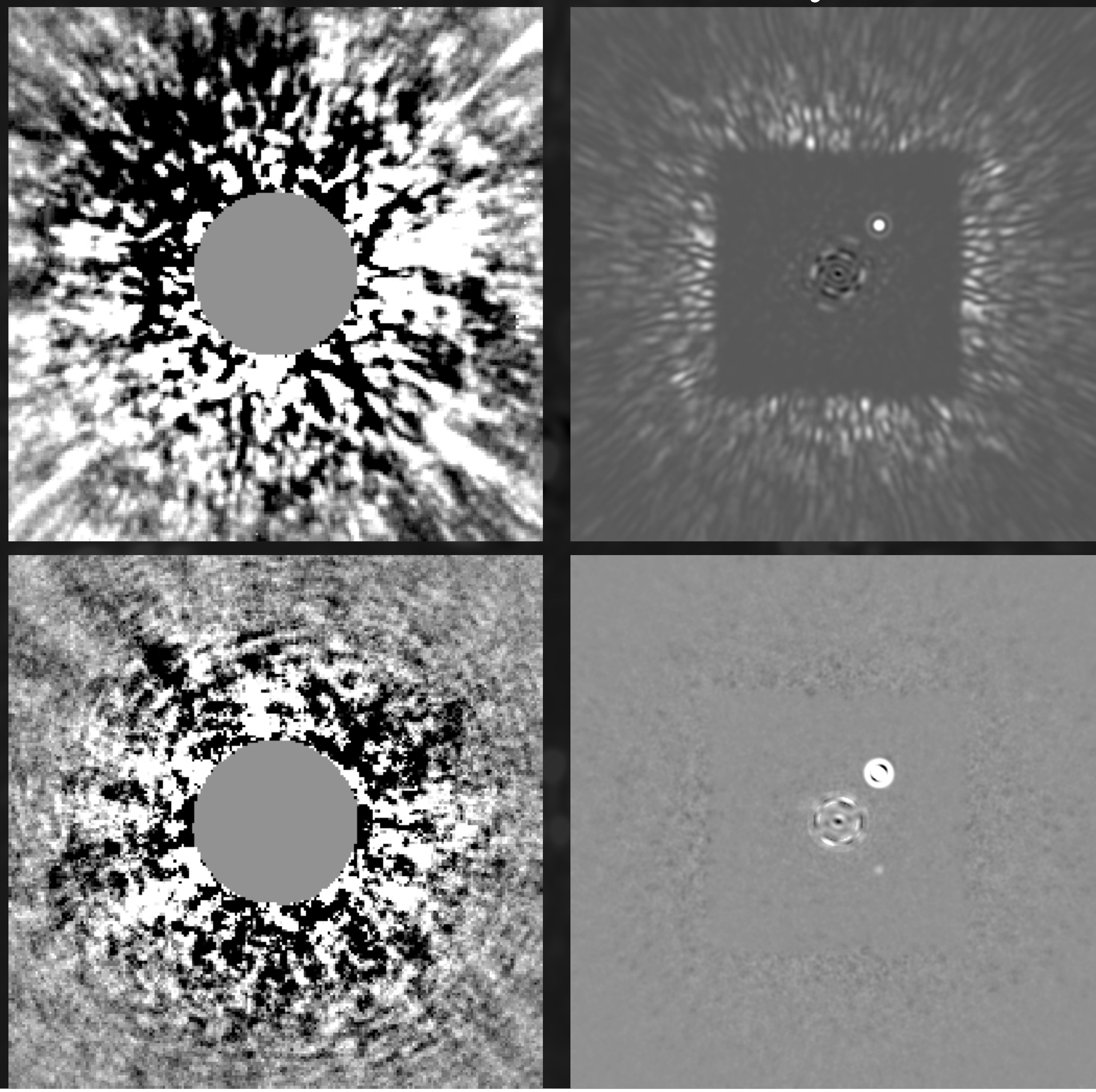

ADI
Raw ATM
Raw static
Photon noise
5σ Detection Limit (Δ mag)
8
10
12
14
16
18
20
5
10
15
20
25
30
35
Angular Separation (λ/D)

GPI vs Altair

Now | In 4 years…

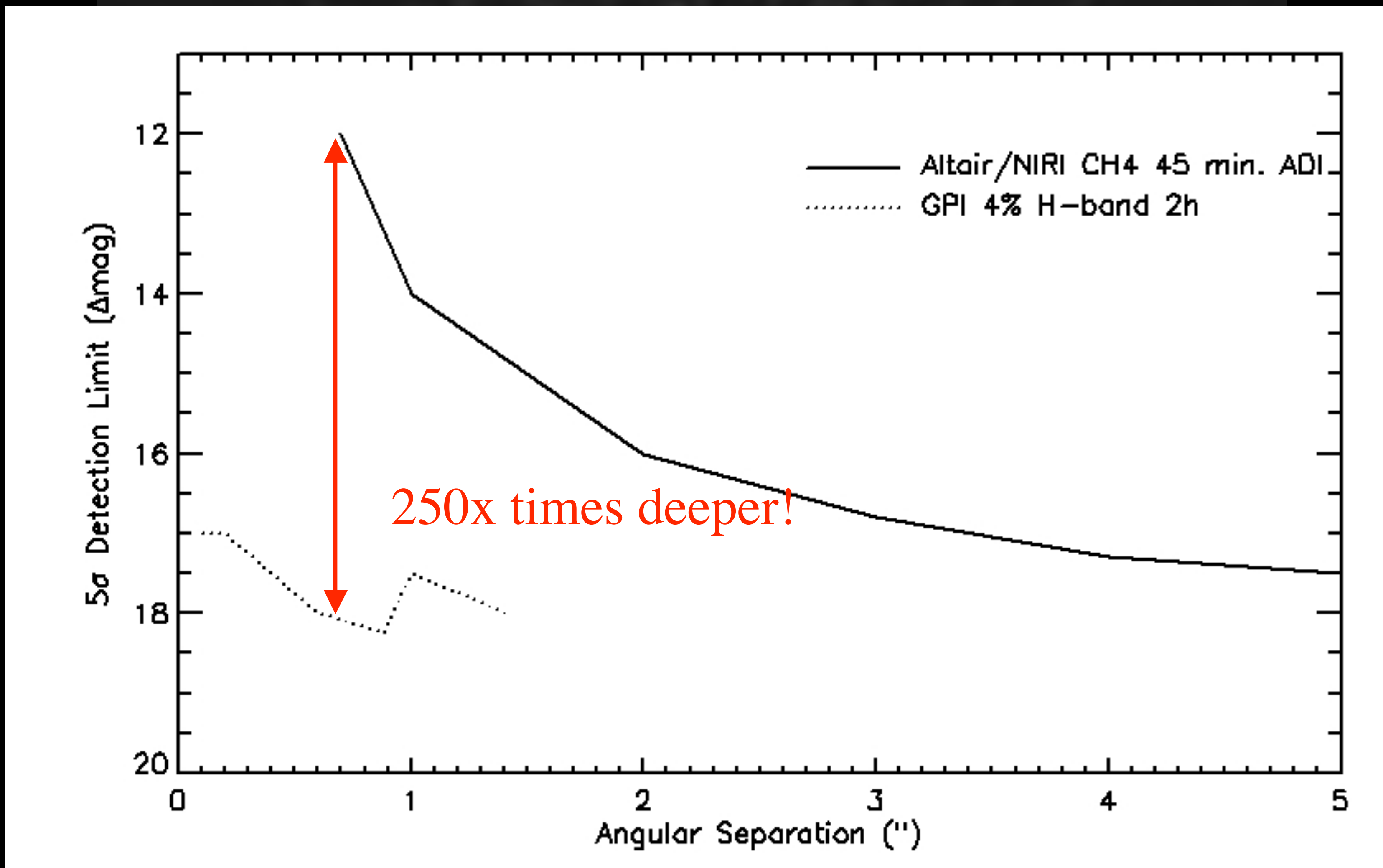
Altair PSF
1.57 microns
CH4 band
4”x4” FOV.
Quasi-static speckle noise limited
Inner region
is saturated.
± 1E-5 linear

Altair & ADI
45 minutes.
± 5E-7 linear



GPI PSF

GPI +
ADI &
SSDI
2h integ



Altair/NIRI CH4 45 min. ADI
GPI 4% H-band 2h
250x times deeper!
5σ Detection Limit (Δmag)
12
14
16
18
20
0
1
2
3
4
5
Angular Separation (")

Conclusion

Speckle noise attenuation techniques well implemented in various projects, from ground-based to space-based!

SSDI: **HARD** - can be limited by non-common path optics, Fresnel propagation effects & coronagraph chromaticity. Good for near pupil-plane aberrations.

ADI: **EASY** - Reference PSF constructed at the same wavelength with FOV rotation. Limited by time evolution of the quasi-static speckle noise.

Speckle symmetry: ???

Future dedicated high-precision instruments (GPI & SPHERE) should be able to bring high contrast to the next level by combining ADI, SSDI, speckle symmetry, super-smooth optics, coronagraph and AO.